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Tribochemistry and Wear Life Improvement in Liquid-Lubricated H-DLC-Coated Bearings

25 July 2007

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Michael Zambrana
SMC/EA

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14. ABSTRACT

In contrast to typical DLC coatings, hydrogenated DLC (H-DLC) coatings exhibit extremely low friction in vacuum and dry atmospheres, suggesting their potential importance for spacecraft applications. We have conducted a study of H-DLC-coated steel thrust bearings, lubricated with a multiply-alkylated cyclopentane oil, either unformulated, or formulated with lead naphthenate or an aryl phosphate ester mixture. Data on uncoated steel thrust bearings were obtained for comparison. The surface chemistry of the additives on worn H-DLC surfaces was evaluated along with chemical analysis of the residual lubricant. In contrast with results on uncoated steel bearings, minimal additive-based tribofilm formation was detected on the surfaces of the H-DLC coatings in the wear tracks. The results indicate that additives optimized for steels may not be appropriate for H-DLC coatings. Although there were indications that H-DLC coatings increase endurance, the high roughness of the bearings contributed to statistical uncertainty. Future studies are planned with higher quality bearings.

15. SUBJECT TERMS

Diamond-like carbon, Spacecraft lubrication, Ball bearings, Tribochemistry, Lubricant additives, Friction and wear testing

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Tribochemistry and Wear Life Improvement in Liquid-Lubricated H-DLC-Coated Bearings

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Introduction

- The hardness and low friction of hydrogenated diamond-like carbon (H-DLC) coatings in dry atmospheres show promise for spacecraft applications
  - Unlubricated: Ideal for devices such as release mechanisms, latches, pointing mechanisms
    - Low temperature devices, and contamination-sensitive devices
  - Lubricated: Ball bearings for solar array drives, wheels/gyros

- Failure in liquid lubricated bearings is usually due to lubricant loss or degradation
  - Use of DLC precludes metal-to-metal contact, possibly reducing degradation
  - Oils and additives are optimized for steels; are they the best for DLC?
    - Alkyl phosphates: Antiwear additive reacts → Fe phosphates
    - Pbnp: Extreme pressure additive reduces → Pb, Pb-C-O tribopolymer

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Goals of this Study

- Primary Goal: Investigate how lubricant additive chemistry varies between steel and H-DLC in steel bearings
  - Aryl phosphate ester mixture
  - Lead Naphthenate

- Secondary Goal: Demonstrate improved endurance and performance of H-DLC-coated bearings compared to uncoated bearings

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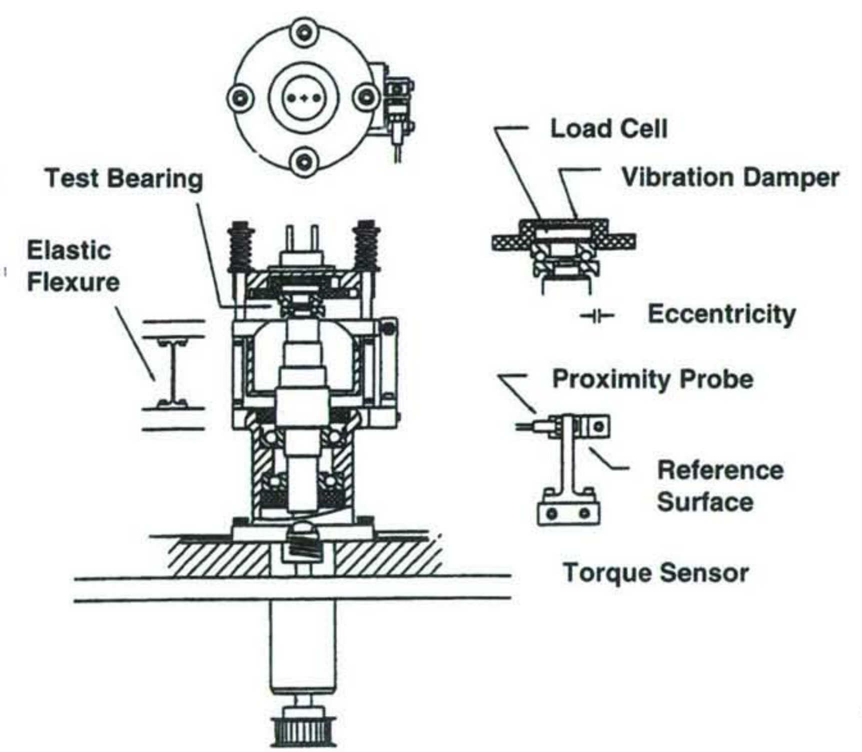
Eccentric Bearing Lubricant Tester (Operated in Non-Eccentric Mode)



- Liquid lubricant, multiply-alkylated cyclopentane (MAC) synthetic hydrocarbon oil (aka Pennzane)
  - NSO 2001 oil with 2% aryl phosphate ester mixture
  - MAC with 3% Pbnp
  - NSO 2001A oil (unformulated)
- Vacuum 1×10^{-6} Torr
- Ball bearing raceways were 1117 steel, coated with hydrogenated DLC or uncoated (balls are 52100 steel)
- The raceway surface was high (R_a>10 μin, R_z ~ 50-75 μin)
  - Bearings used in space typically have much lower roughness
  - Roughness tended to drop after DLC coating

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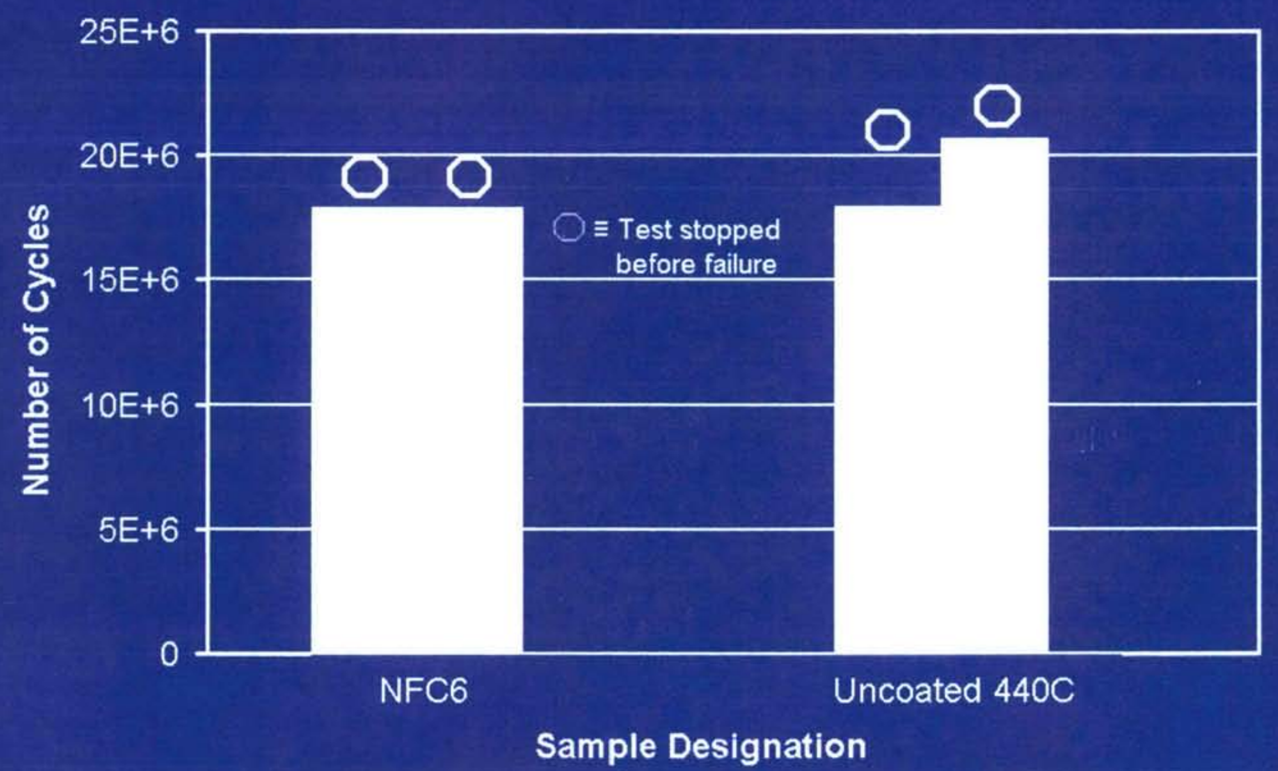
H-DLC-Coated Thrust Bearing Testing Summary
Tested using MAC oil (Pennzane) w/ Pbnp



- **No Failure seen with either coated or uncoated bearings**
  - **Tests were stopped after 18-20 Mcycles**

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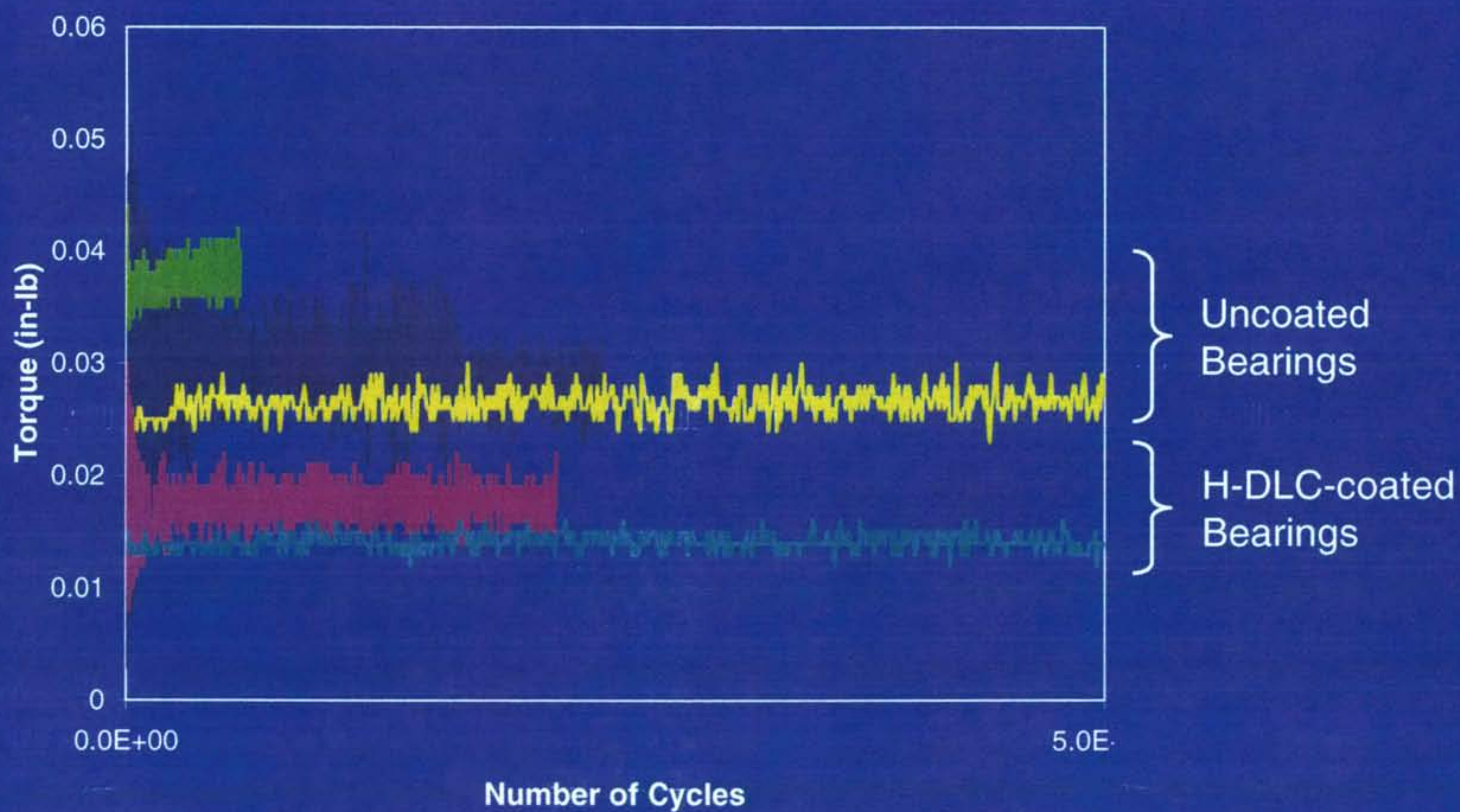
Torque of Thrust Bearings
Used with MAC oil (Pennzane) w/ Pbnp



- **Torque is lower for H-DLC-coated bearings than for uncoated bearings**

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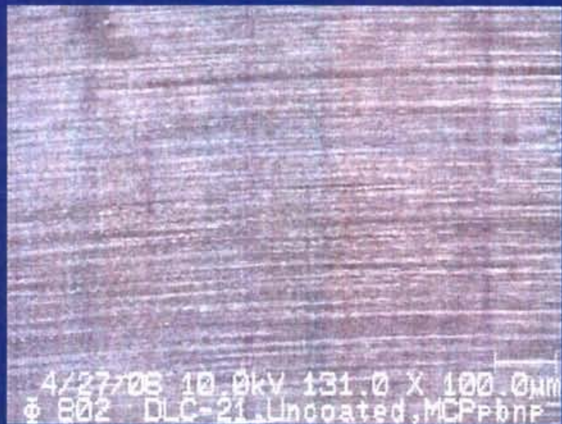
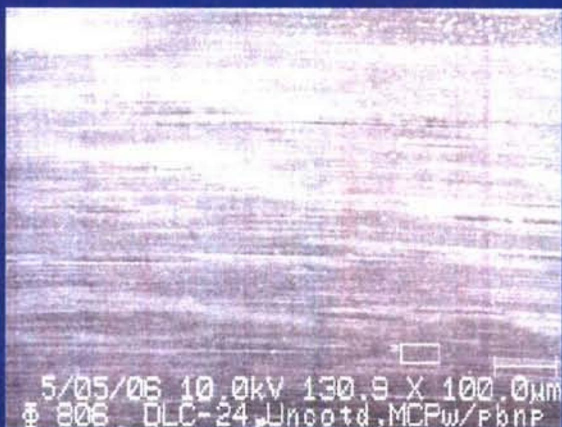
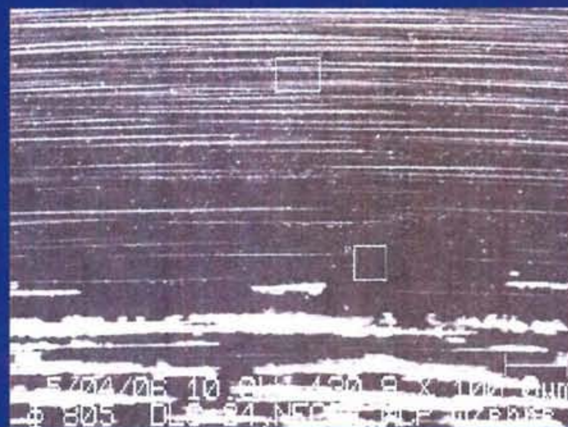
Auger of Thrust Bearings

Used with MAC oil w/ Pbnp – 1.7×10^{7} cycle (no failure)

	Uncoated Bearings	NFC6-Coated Bearings
2 Mcycles		
18 Mcycles		

- Little wear after 2 Mcycles
- Visible wear after 18 Mcycles

- Mild wear of coating after 2 Mcycles
- Coating loss in some areas after 18 Mcycles
  - Mostly near center of wear track

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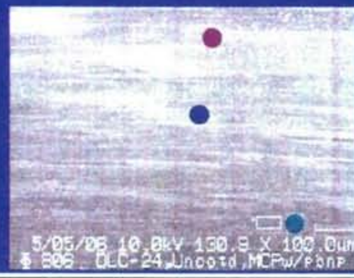
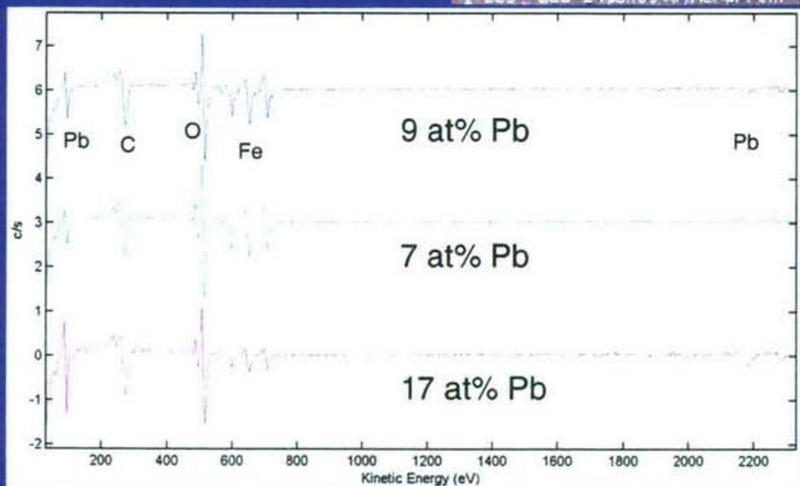
Auger of Thrust Bearings

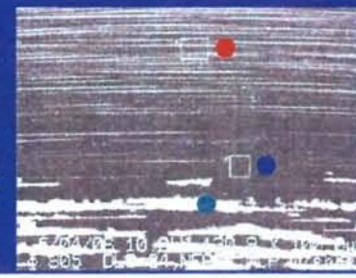
Used with MAC oil w/ Pbnp – 18 Mcycle (no failure)

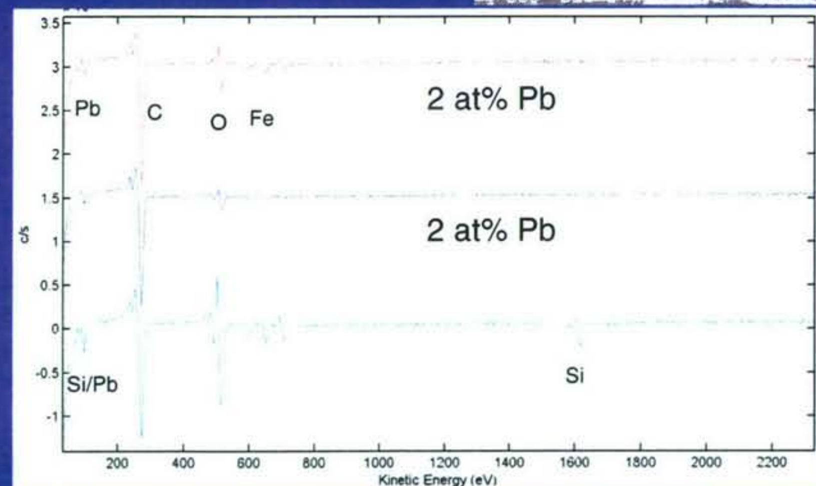
Uncoated Bearing





H-DLC-Coated Bearing





- Significantly more reacted Pb/C/O-containing tribofilm for uncoated than H-DLC-coated bearing
  - Pb concentration on worn and unworn regions of H-DLC-coated bearings similar
  - Indicates that Pbnp undergoes chemisorption, but little tribofilm formation on H-DLC

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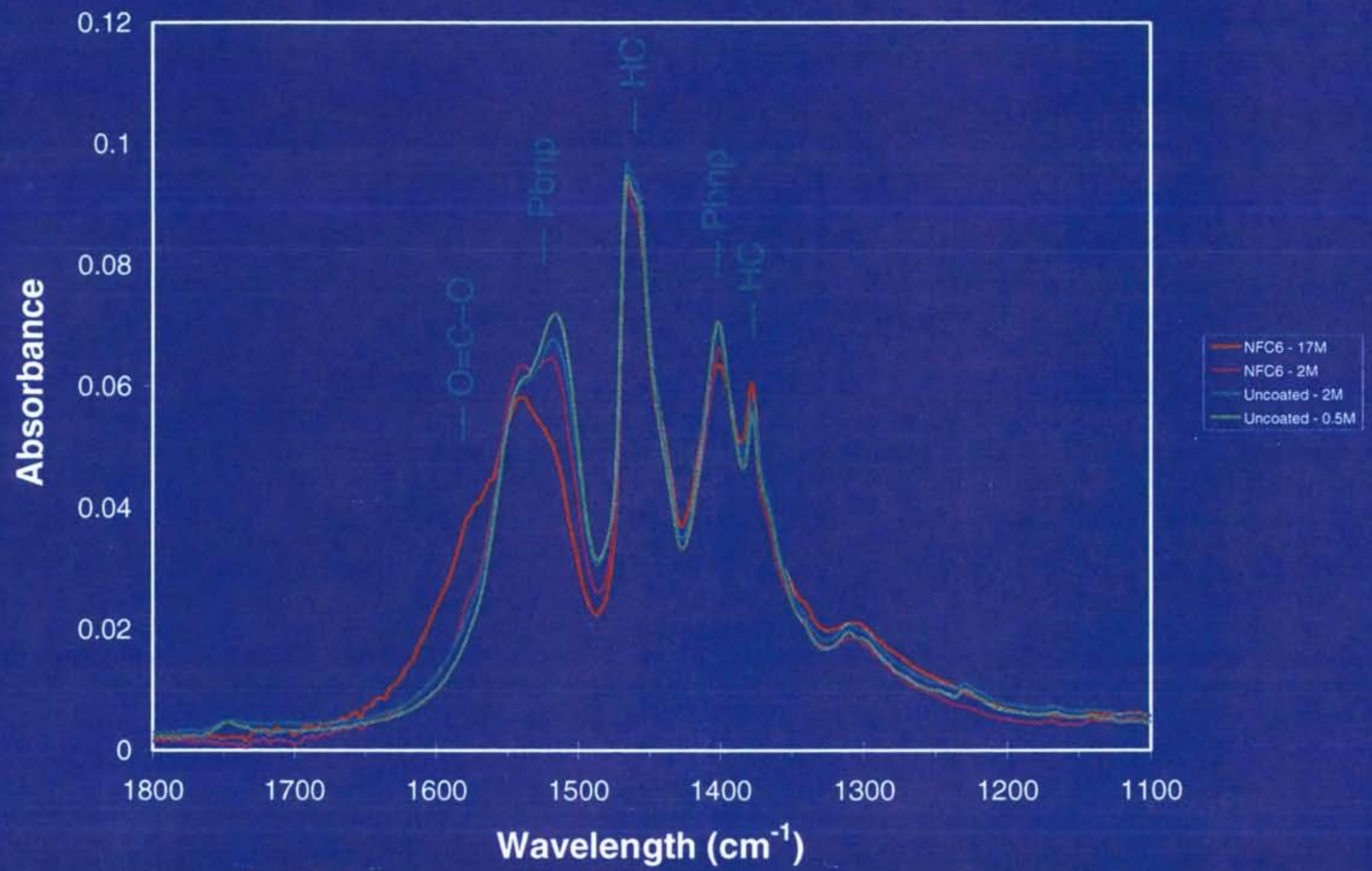
FTIR Results on H-DLC-Coated & Uncoated Thrust Bearings

Tested using MAC oil w/ Pbnp



- Pbnp in oil appears to break down with increasing running time
  - Regardless of tribofilm deposition (I.e., compare Auger of coated and uncoated samples

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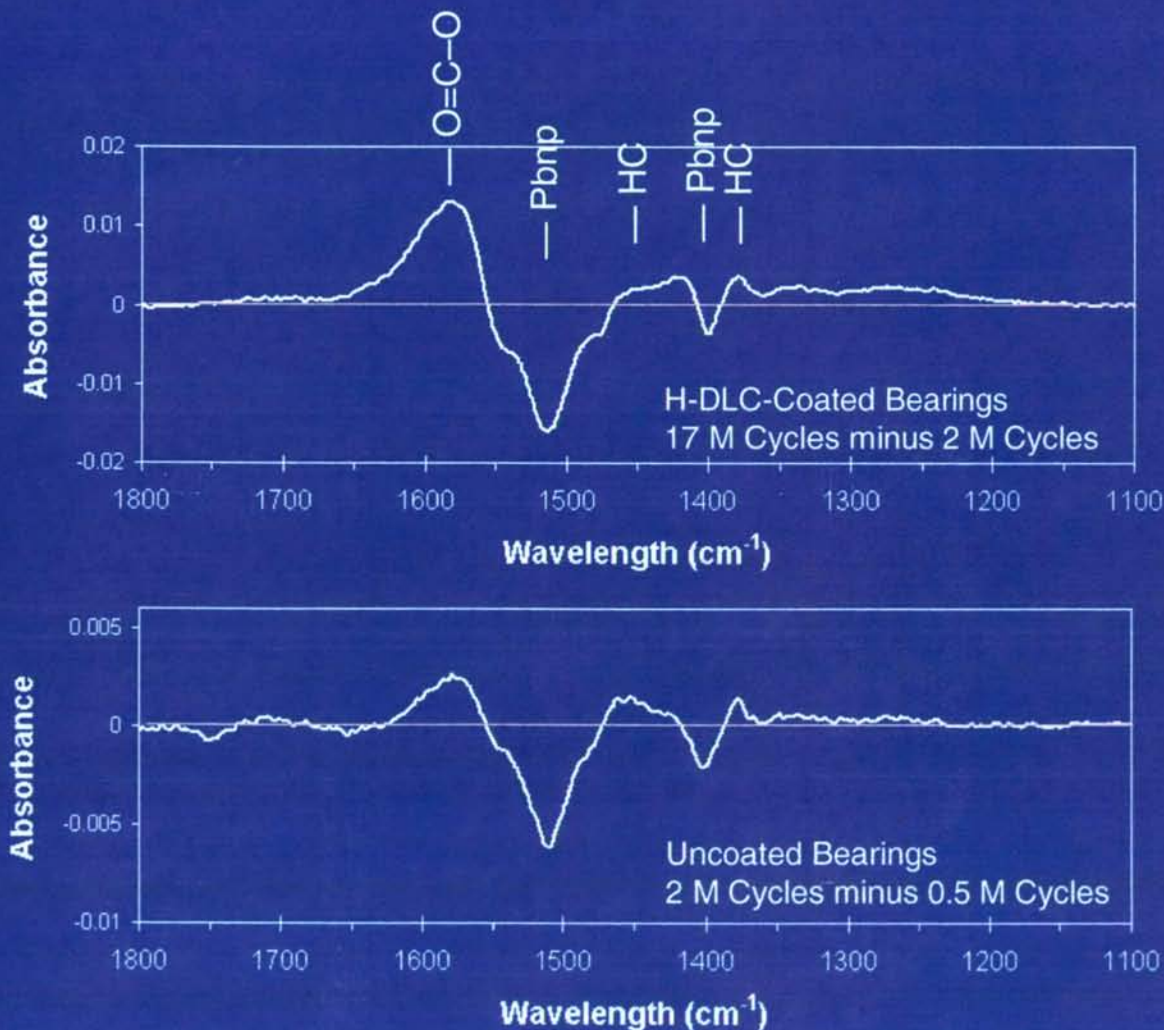
FTIR Difference Spectra

H-DLC-Coated & Uncoated Thrust Bearings, Tested using MAC oil w/ Pbnp



- Confirms that Pbnp in oil breaks down with increasing running time
  - Reduction of unreacted Pbnp peaks
  - Increase of breakdown product of Pbnp, $-CO_2$

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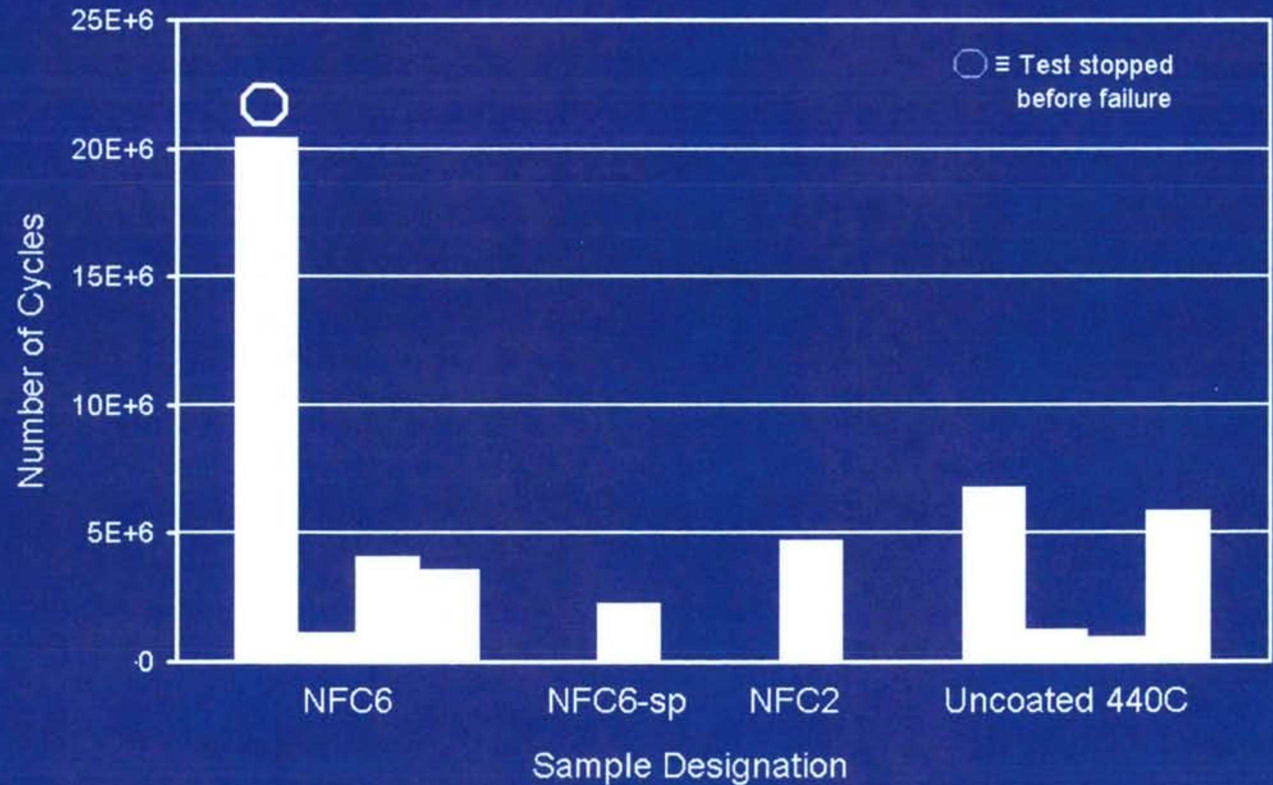
H-DLC-Coated Thrust Bearing Testing Summary

Tested using NSO2001 Oil (Pennzane w/ Phosphate Additives)



- **All samples failed except one H-DLC sample (NFC6), which was stopped after 20,000,000 cycles**
  - **Indicates that H-DLC *can* provide significantly longer life with NSO2001**
  - **Variation likely due to high roughness of bearings**

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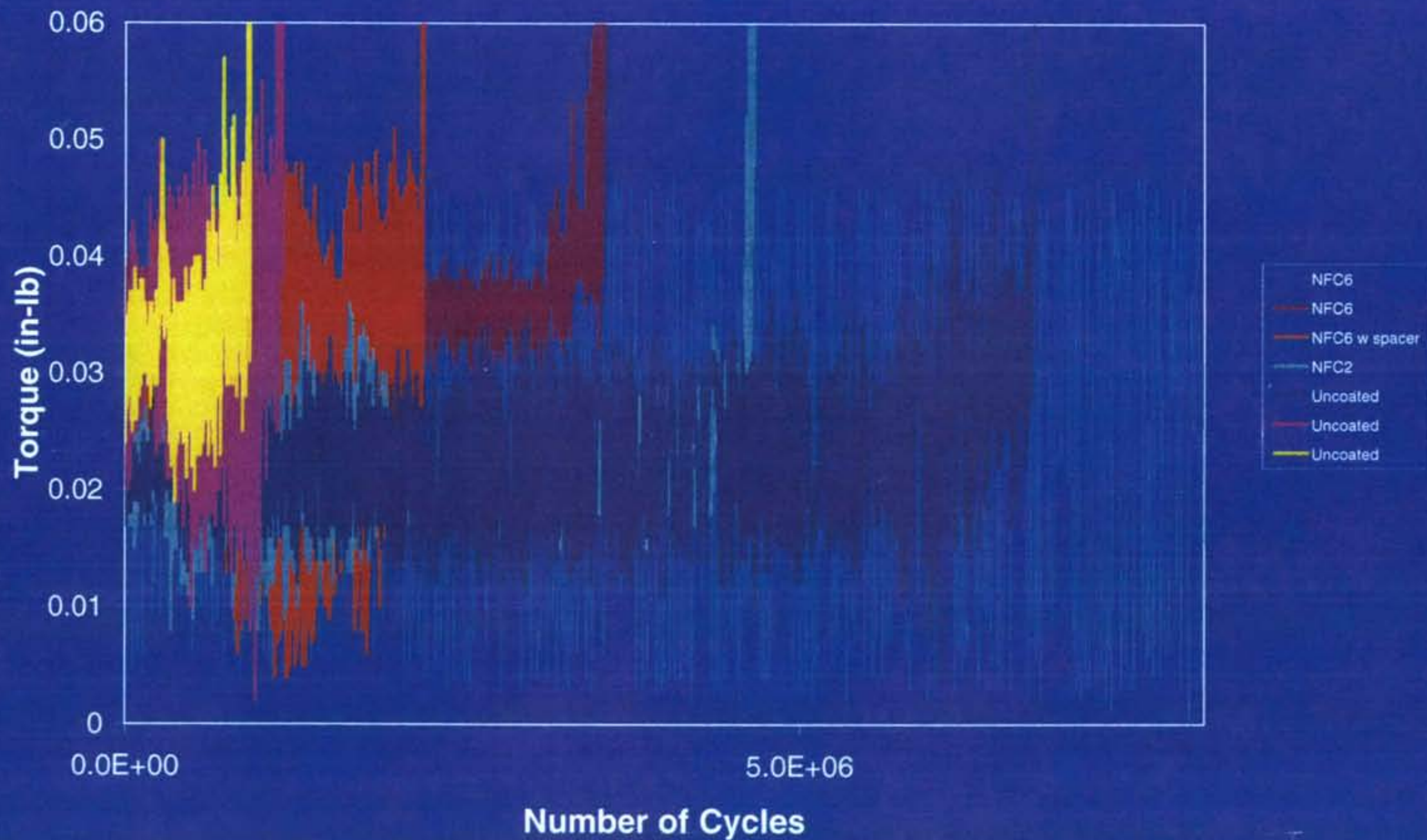
Torque of Thrust Bearings

Tested using NSO2001 Oil (Pennzane w/ Phosphate Additives)



- Torque does not appear to correlate with presence of H-DLC coating
  - Tribofilm is much thinner with phosphate esters than for Pbnp

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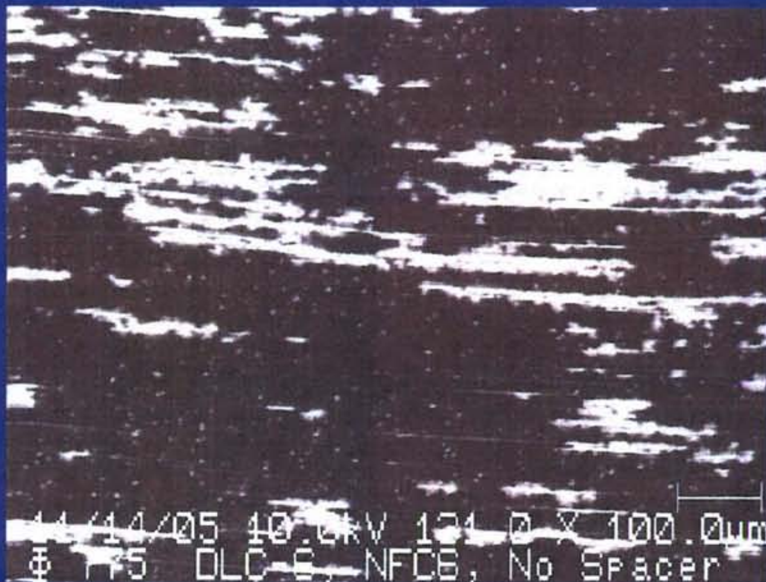
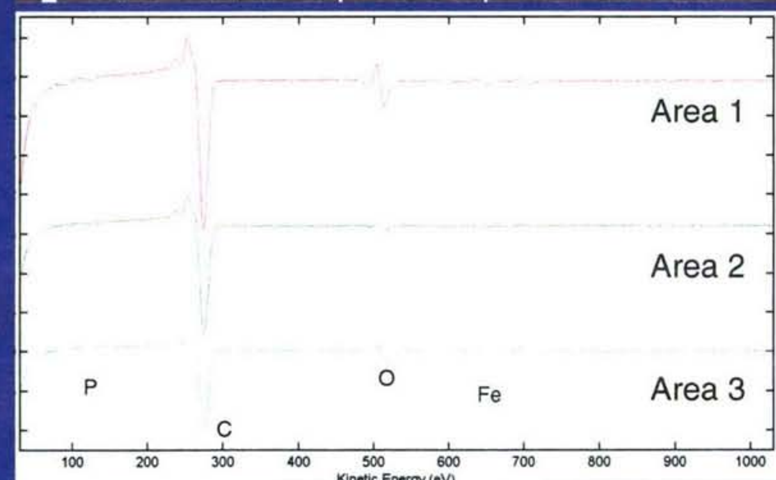
SEM/Auger on H-DLC-Coated (Unfailed) Thrust Bearing

Tested using NSO2001 Oil – 20 Mcycle (no failure)





- 20% Wear/delamination near center of ball track
- High carbon in delaminated areas: tribofilm deposition
  - 0.2-0.5 at% P detected in delaminated areas
    - Similar to uncoated disk: ~0.3 at% P and high C (not shown)
  - P virtually undetectable in coated areas

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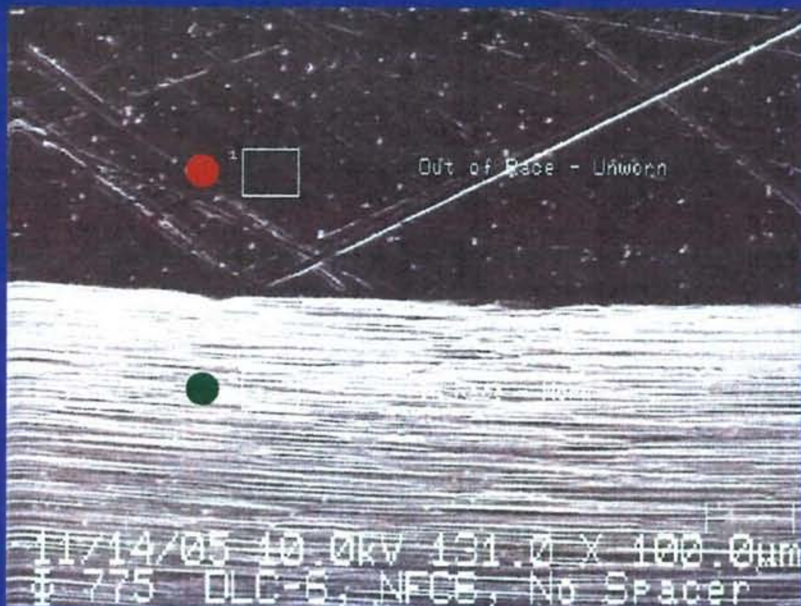
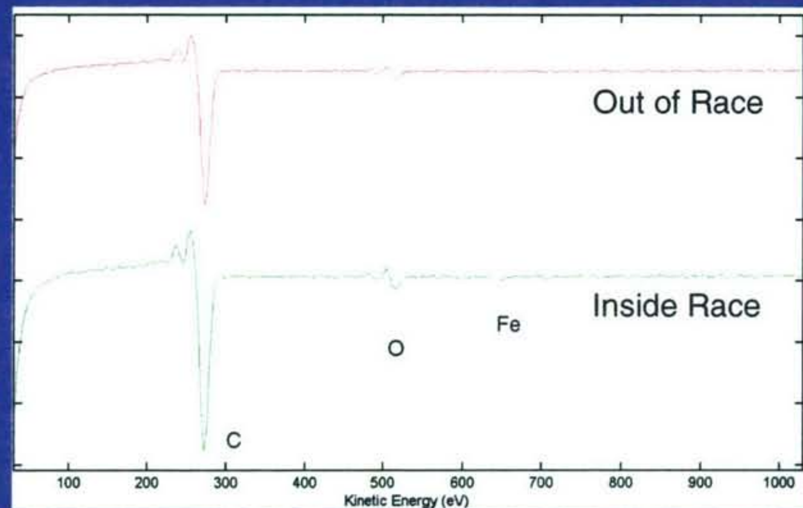
SEM/Auger on H-DLC-Coated (Unfailed) Thrust Bearing

Tested using NSO2001 Oil – 20 Mcycle (no failure)





- Outside of center of wear track, most of H-DLC coating is intact after successful test
- P is virtually undetectable in both areas

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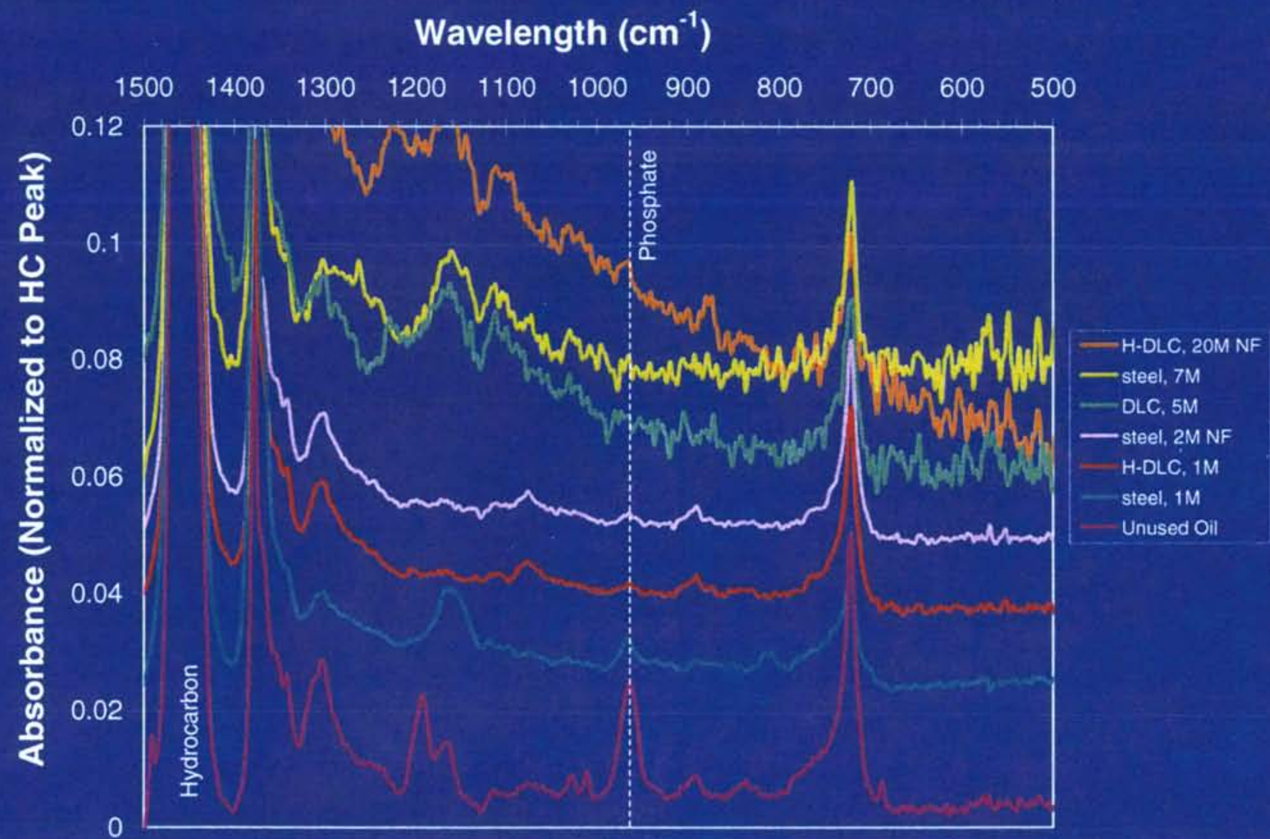
FTIR Results on H-DLC-Coated Thrust Bearings

Tested using NSO2001 Oil



- Degradation of aryl phosphate additives in remaining oil
  - No significant differences between oils from uncoated and H-DLC-coated samples, or between oils from failed and unfailed H-DLC-coated samples
  - Degradation of phosphate additives related only to number of cycles

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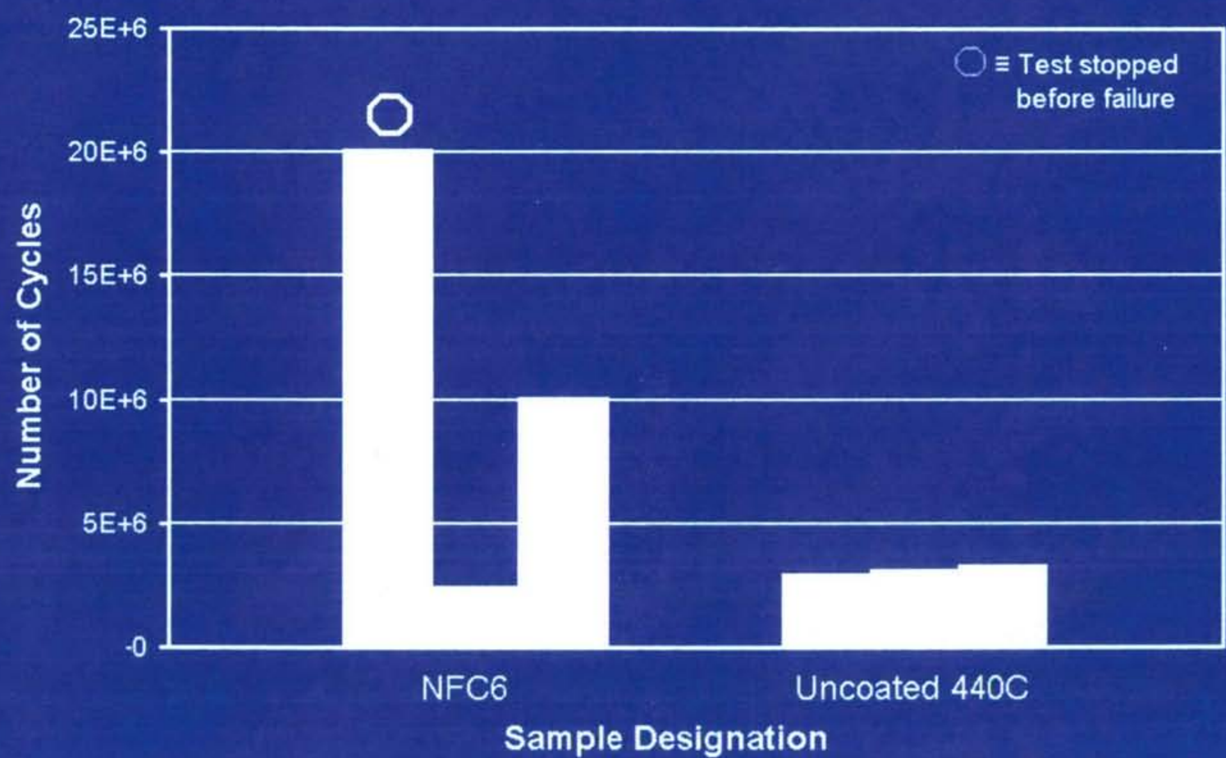
H-DLC-Coated Thrust Bearing Testing Summary
Tested using NSO2001A Oil (Unformulated)



- H-DLC samples appeared to exhibit greater endurance, including one sample that did not fail

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Summary of H-DLC-Coated Thrust Bearing Results

- Multiply-alkylated cyclopentane (MAC) oil - Pennzane formulated with lead naphthenate (Pbnp)
  - Less deposition of Pb/C/O-containing tribofilm on H-DLC than uncoated steel
    - Agrees with Carré, Bertrand, Lince, Tribology Letters, 16(3) (2004) 207: Redox reaction of Pbnp requires metal-to-metal contact
  - Lower torque for H-DLC compared to uncoated steel. Possible reasons:
    - Lower friction of H-DLC ($\mu<0.01$) as opposed to steel ($\mu>0.3$)
    - Lower roughness of coated surface
    - Less deposition of Pb-containing tribofilm (lower wear, but higher μ?)
  - Inconclusive results on endurance: All tests stopped at 18-20 Mcycles before failure occurred

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Summary of DLC-Coated Thrust Bearing Results

- NSO2001 - Pennzane with synthetic phosphate esters
  - Less deposition of P/C-containing tribofilm on H-DLC than uncoated steel
    - P-containing additive coatings detected only where H-DLC delaminated
  - Disappearance of aryl phosphate additives in oil in both uncoated and H-DLC-coated cases
    - Degradation of aryl phosphate additives related to cycle time, but not to presence of coating or whether failure occurred
  - Potential for increased endurance when using H-DLC coatings

- NSO2001A – Unformulated Pennzane
  - H-DLC-coated samples showed statistically greater performance than uncoated samples, possibly due to
    - Lower roughness
    - Lower lubricant degradation
  - Better performance than with aryl phosphate additives
    - Additives degrade H-DLC coating?

- Testing on bearings with lower surface roughness will begin shortly

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Part II – Effect of Environment on Friction of Hydrogenated DLC Coatings

- Hydrogenated DLC has shown very low friction and wear in vacuum use, higher friction in atmosphere

- Effect of environment critical for spacecraft applications
  - Most "inert" test environments are created by purging with N_2 to minimize H_2O and O_2, but RH ~ 1%, O_2 ~ ?
  - What level of H_2O, O_2, and other impurities cause changes in tribology?

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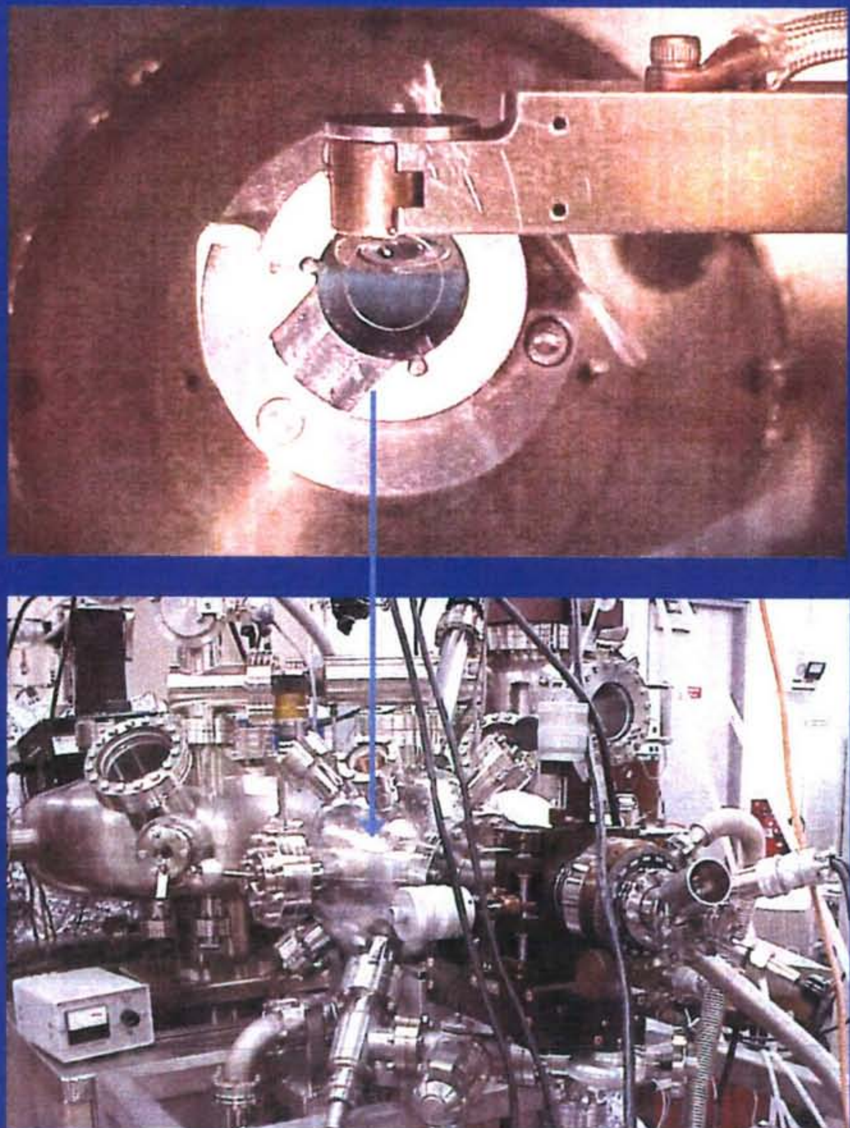
Ultrahigh Vacuum Tribometer



- Ball on disk contact geometry
- Nominal sizes 3/16” ball, 0.55” disk
- UHV sample transfer to analysis chambers
  - XPS, HREELS, AES, Mass spectrum
- Controlled exposure to gases - operational pressure range $<1 \times 10^{-9}$ Torr to ambient
- Simultaneous measurement of friction and load with orthogonal strain gages
- Possible load range 10mN to >10 N
- Contact stresses from ~150MPa to >1GPa, material and ball size dependent
- Typical sliding speed, 1 cm/sec

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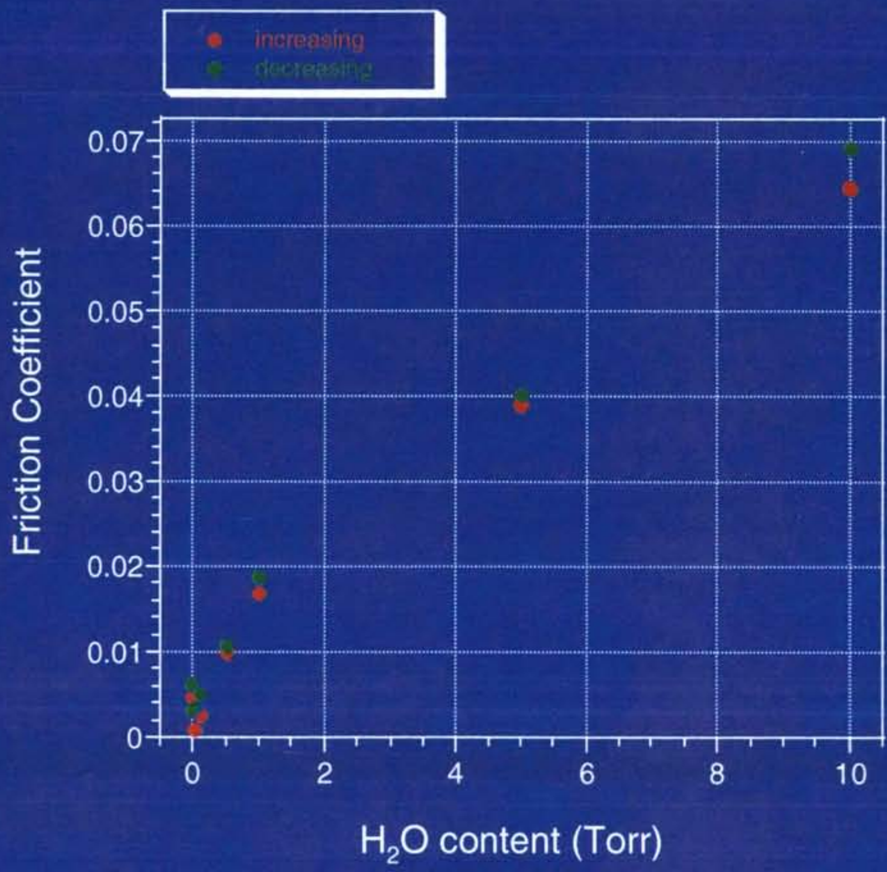
Effect of Relative Humidity on Friction

H-DLC coated steel ball sliding on H-DLC coated steel plate



- Hydrogenated DLC coatings have extremely low friction in UHV
- The friction coefficient increases with increasing water vapor pressure in the test chamber.
- This trend is the opposite of that for non-hydrogenated DLC.

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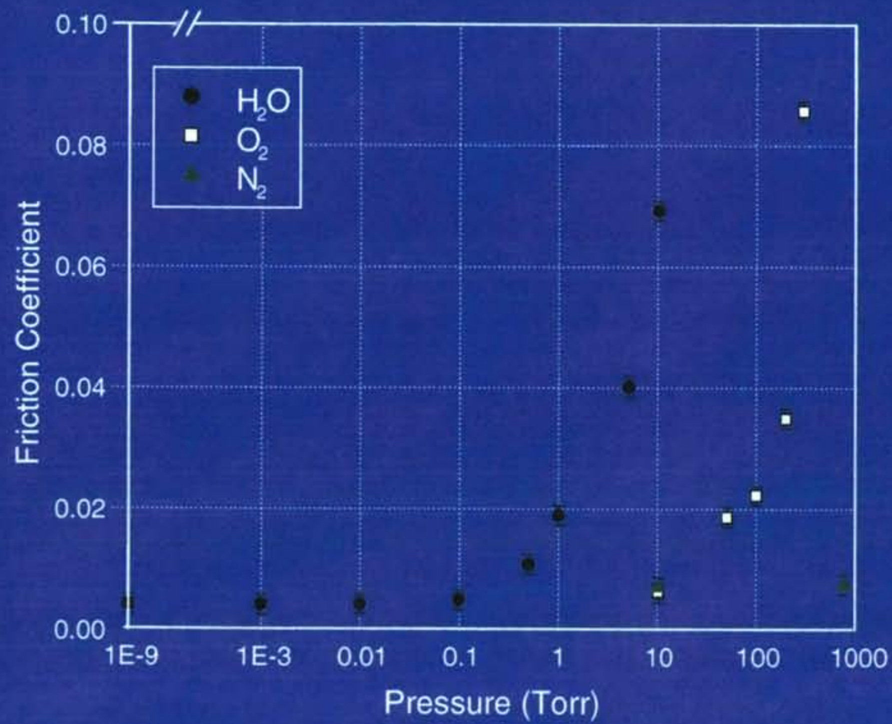
Effect of Relative Humidity on Friction

H-DLC coated steel ball sliding on H-DLC coated steel plate



- O_2 does not begin affecting friction until a pressure two orders of magnitude higher than H_2O, but has similar effect
- Purified N_2 has negligible effect on friction

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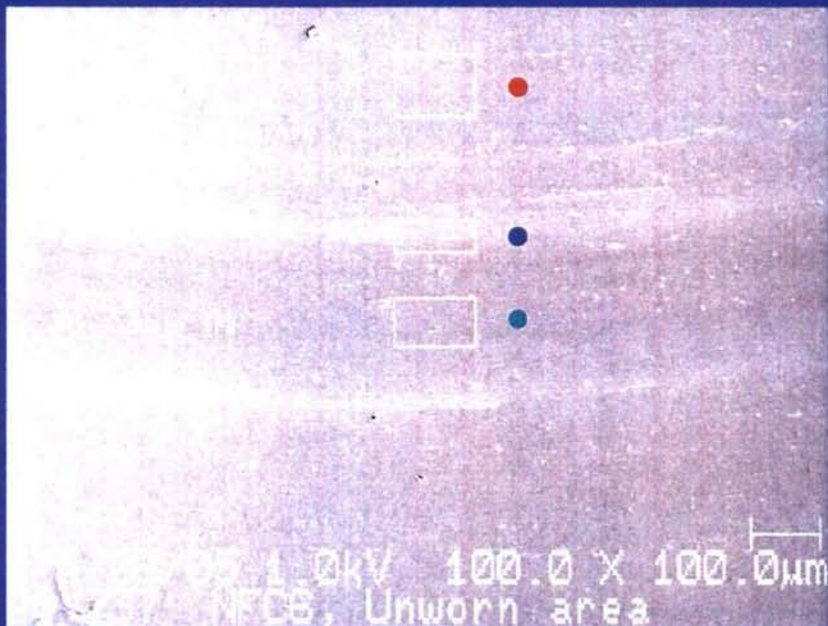
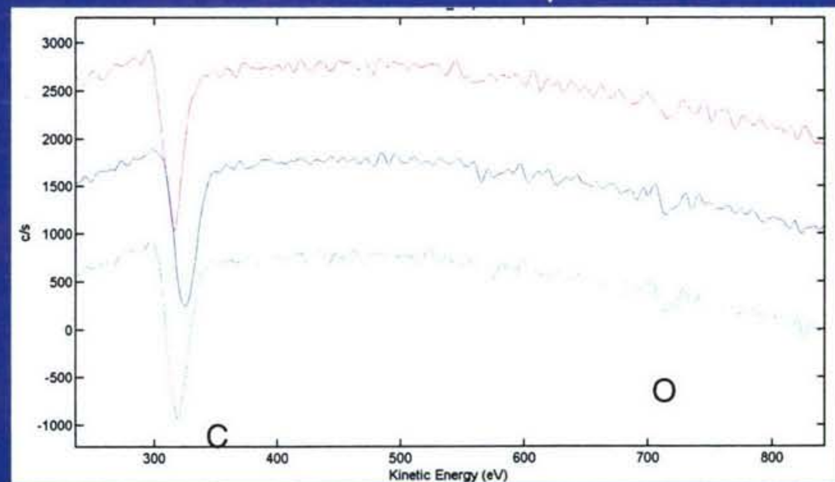
Auger Spectroscopy of Wear Track for H-DLC sliding on H-DLC in 300 Torr O_2





- No apparent difference in surface chemistry between worn and unworn regions
  - Detected oxygen due to small amounts of adsorbed O or OH from atmosphere

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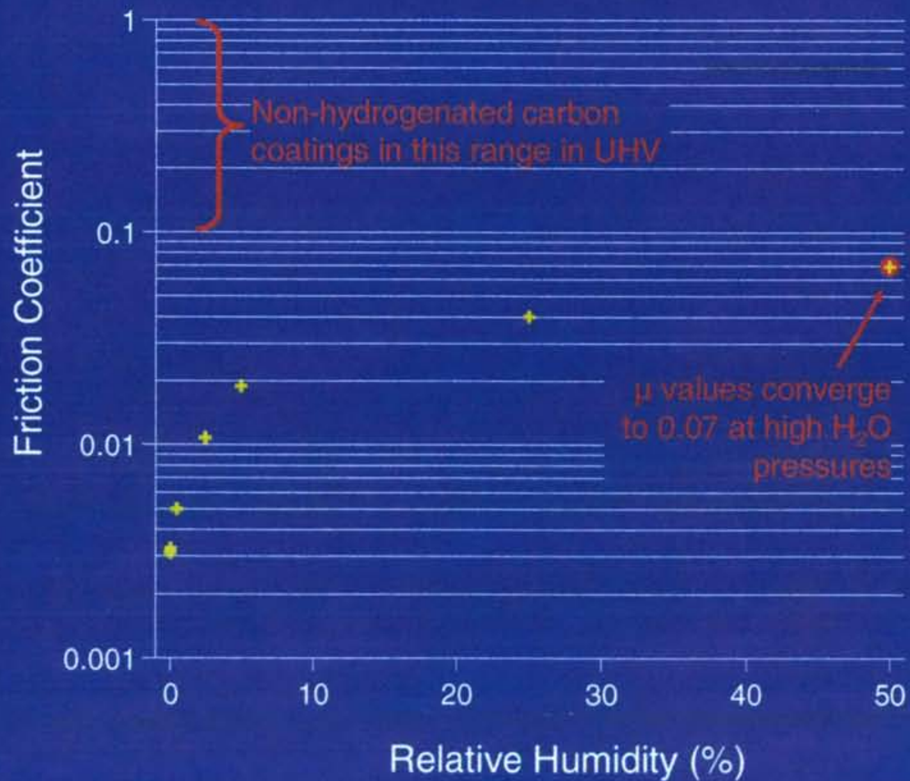
The Effect of H_2O on Different Carbon Coatings
Hydrogenated vs. Non-hydrogenated



- Hydrogenated and non-hydrogenated carbon coatings have very different friction in UHV
- The converging friction properties under humid environments suggest a common lubrication mechanism by water. [Kim, Lince, Eryilmaz, Erdemir, Tribol. Lett., 21(1) (2006) 51-56.]

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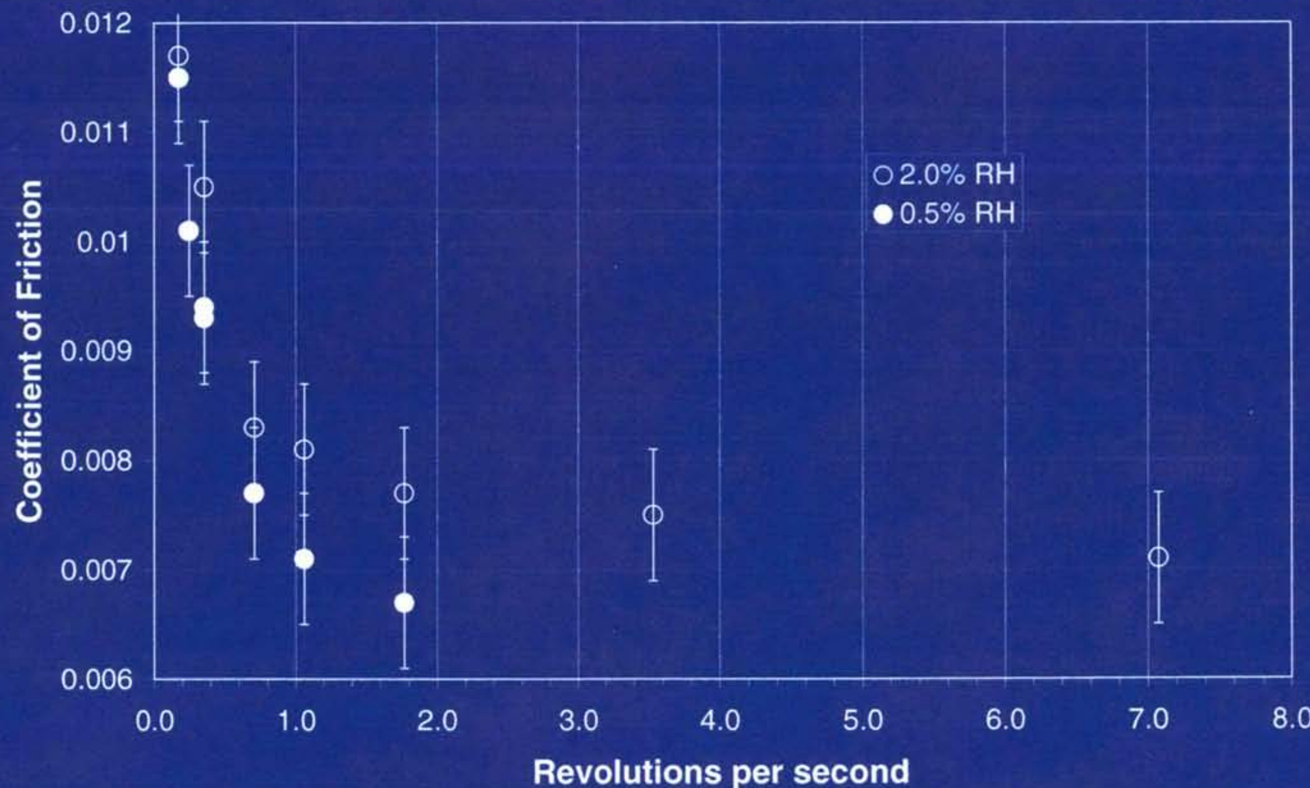
Pin-on-Disk Tribometry of H-DLC

Variation of Friction with Rotation Speed and Humidity



- **Friction highly dependent on rotation speed**
  - **Water molecules weakly absorbed; displaced by sliding contact**
  - **Slower speeds allow greater water absorption between passes**
- **Weak effect on increasing humidity**

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Conclusions

- The use of H-DLC coatings for liquid-lubricated bearings in spacecraft appears promising, although more data is needed.
  - No apparent tribofilm formation on H-DLC-coated bearing surfaces
  - Future testing will be done on bearings with lower roughness
- Tribological properties of H-DLC coatings are significantly affected by small amounts of H_2O and O_2 impurities in “dry” N_2 environments.
  - Careful attention is needed for spacecraft mechanisms tested in “dry” N_2 for vacuum applications.

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